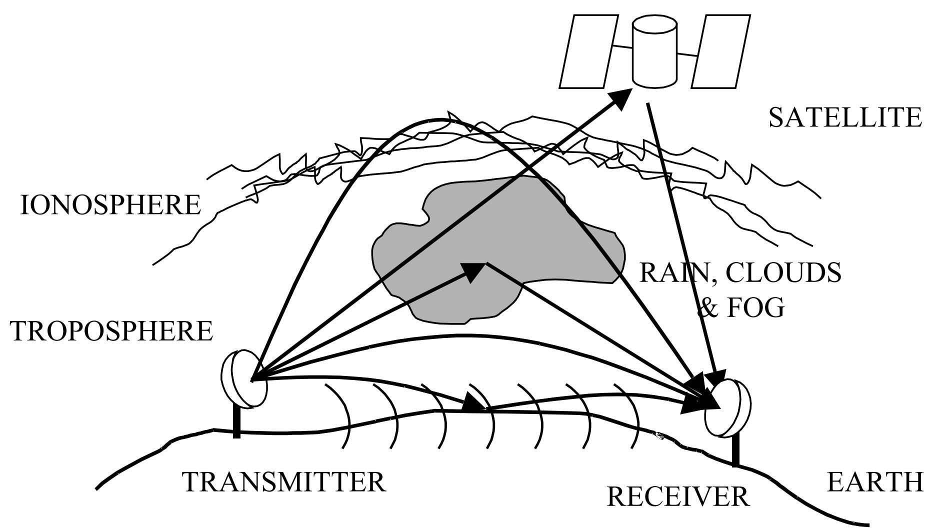
EO2652
Fields, Waves and Electromagnetic Engineering

INTRODUCTORY NOTES

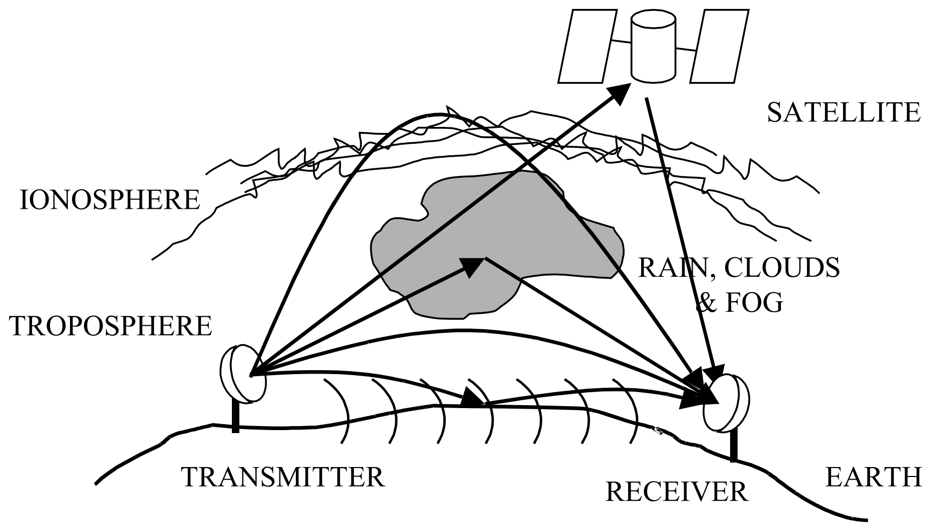


Communication Systems & Networks (1)

- Telecommunications refers to communications systems and networks that transfer information from a transmitter (sender) to a receiver across a distance.
- The information is sent and received as signals, which are electric (or more generally, electromagnetic) representations of the data.
- The information can be voice, data, video, images or combinations (i.e., multimedia).
- Data can be sent one way (simplex), two-way, but only one direction at a time (half duplex), or two way simultaneously (full duplex).
- The native (original) form of the data or signal can be
  1. analog: continuously varying in time (e.g., audio, temperature and pressure data),
  2. digital: sequence of voltage pulses (e.g., computer data, text and integers).
- The medium can be:
  1. a physical structure (e.g., transmission line or optical fiber): guided, wired or cable
  2. free space: wireless or unguided.

Communication Systems & Networks (2)

- Example of a free-space (wireless) communication channel:

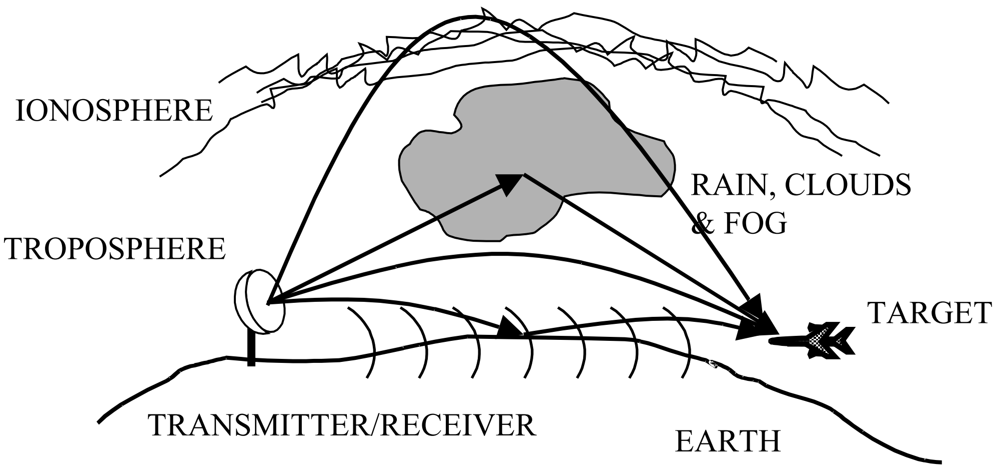


- Note that for two-way communications each endpoint has a transmitter and receiver.
- Lines are called "rays" and depict the propagation paths of electromagnetic waves.
- Some propagation mechanisms are illustrated: ground wave, multipath (reflection from the ground), ionospheric reflection[1], tropospheric scattering, and refraction (bending).

[1] The ionosphere refers to the upper region of the earth's atmosphere, altitudes greater than about 90 km; the troposphere is the lower region near the surface.

Communication Systems & Networks (3)

- Radar is a related topic. A <u>monostatic</u> radar is shown (transmitter and receiver in the same location).



- Bistatic radar refers to the case where the transmitter and receiver are not co-located.
- The same propagation mechanisms apply as for communication systems.
- Both analog and digital radar signals are used.
- Other military applications: electronic warfare (signals intelligence, direction finding, etc.)

Wireless vs. Wired

- Short comparison of wireless and wired systems:

Wireless (free space)	Wired (cable, coax, fiber, etc.)
Bandwidth limited	Wide bandwidth
Power spreading (high gain antennas help)	Low loss
Infrastructure not required	High cost infrastructure
Susceptible to interference and jamming	More secure; less interference
Signals can be intercepted	Interception depends on the type of transmission line. For fiber: no electromagnetic coupling, interference, or hazard

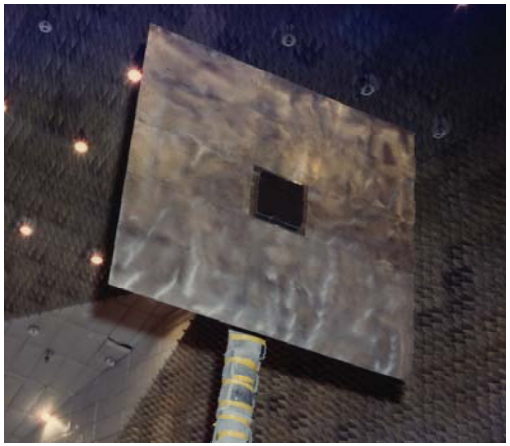
- Typically wireless propagation is in free space, but can include ground and water.

Antennas

"Antenna farm"

"Deep space" communications antenna

Antennas



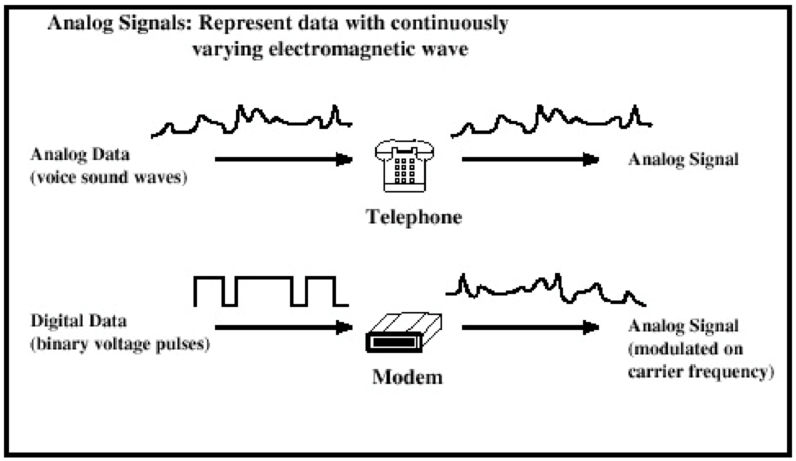
Shuttle tile

Carrier bridge

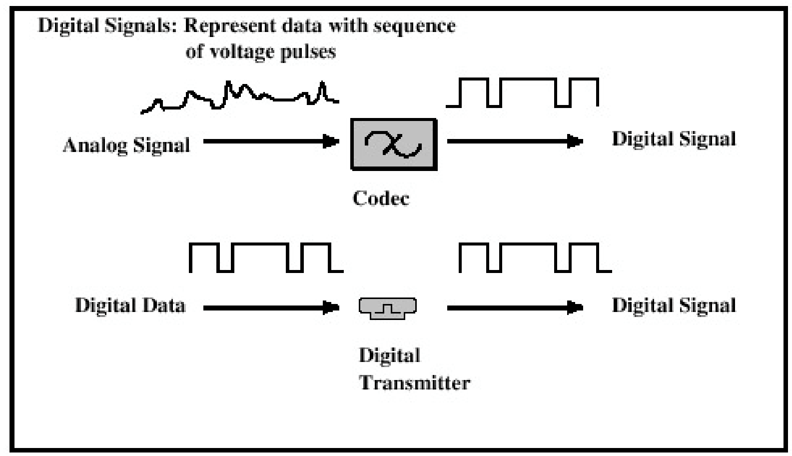
Terrestrial link

Digital and Analog Signals (1)

- Native analog and digital data can be represented by either analog or digital signals



Analog signals out



Digital signals out

(From W. Stallings, *Wireless communications and Networks*, Prentice Hall)

Digital and Analog Signals (2)

Data signals

	Analog Signal	Digital Signal
Analog Data	Two alternatives: (1) signal occupies the same spectrum as the analog data; (2) analog data are encoded to occupy a different portion of spectrum.	Analog data are encoded using a codec to produce a digital bit stream.
Digital Data	Digital data are encoded using a modem to produce analog signal.	Two alternatives: (1) signal consists of a two voltage levels to represent the two binary values; (2) digital data are encoded to produce a digital signal with desired properties.

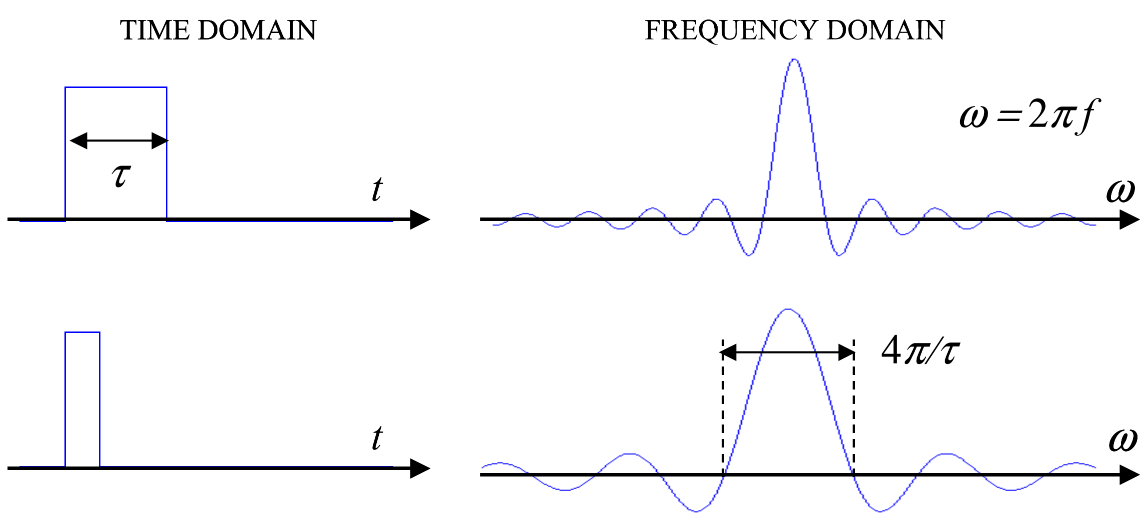
Treatment of signals

	Analog Transmission	Digital Transmission
Analog Signal	Is propagated through amplifiers; same treatment whether signal is used to represent analog data or digital data.	Assumes that the analog signal represents digital data. Signal is propagated through repeaters; at each repeater, digital data are recovered from inbound signal and used to generate a new analog outbound signal.
Digital Signal	Not used	Digital signal represents a stream of 1s and 0s, which may represent digital data or may be an encoding of analog data. Signal is propagated through repeaters; at each repeater, stream of 1s and 0s is recovered from inbound signal and used to generate a new digital outbound signal.

(From W. Stallings, *Wireless Communications and Networks*, Prentice Hall)

Time and Frequency Domains (1)

- The time and frequency domains are two representations of a signal that are related by the Fourier transform and inverse Fourier transform (i.e., the Fourier transform of a time signal gives its frequency domain representation).
- In general, there is an inverse relationship between the spread of a signal on the time and frequency axes: a short time signal has many frequency components; a long time duration signal has fewer frequency components.
- The frequency distribution of the signal is referred to as its spectrum.

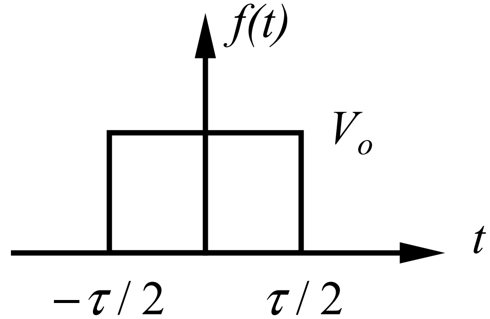


Time and Frequency Domains (2)

- For example, the Fourier transform of a rectangular pulse is a "sinc" function

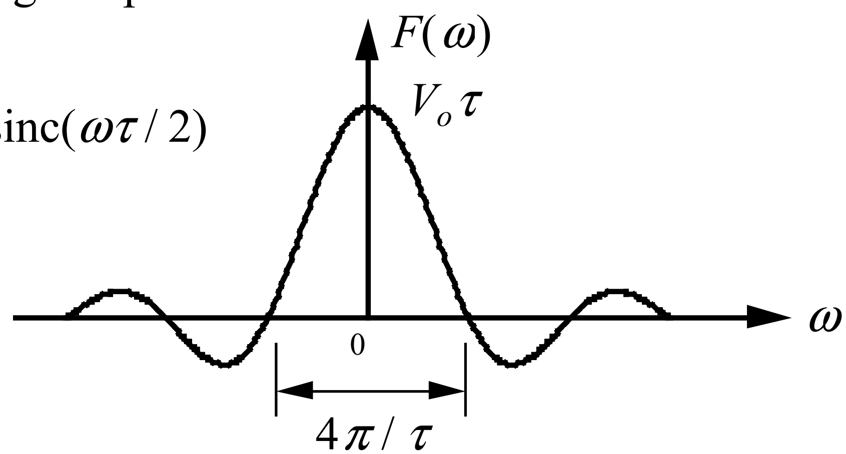
rectangular pulse

$$f(t) = \begin{cases} V_o, & |t| < \tau/2 \\ 0, & \text{else} \end{cases}$$



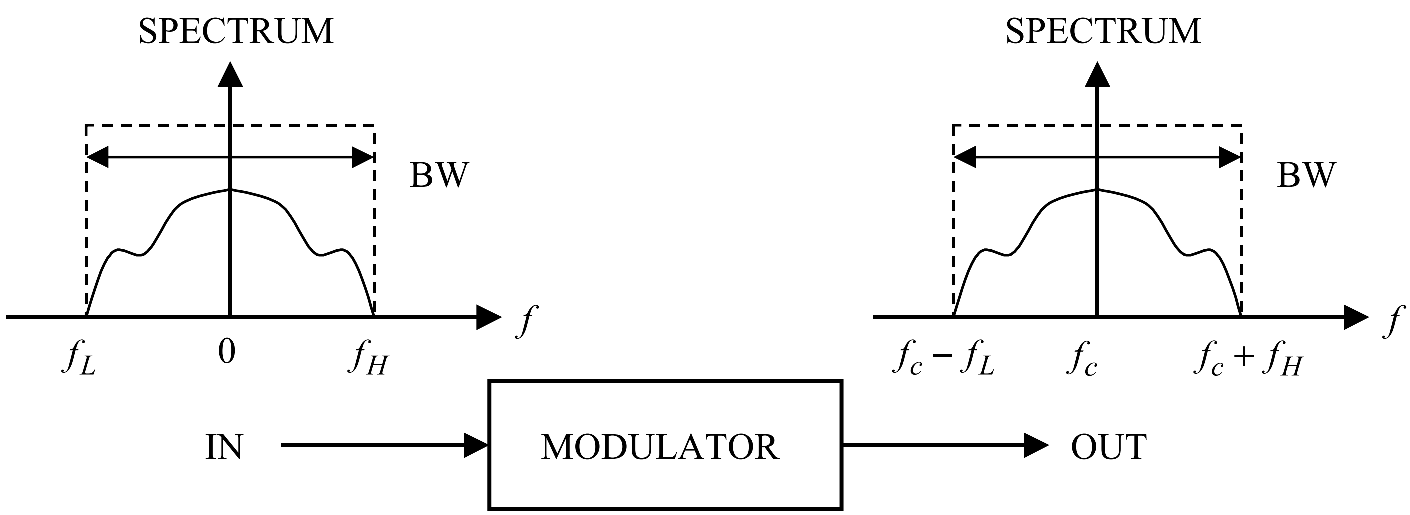
Fourier transform of the rectangular pulse

$$F(\omega) = V_o \tau \frac{\sin(\omega\tau/2)}{\omega\tau/2} \equiv V_o \tau \,\mathrm{sinc}(\omega\tau/2)$$



Time and Frequency Domains (3)

- The signal's spectrum is centered at zero frequency, $f = 0$ (also referred to as dc or baseband)
- Frequencies near dc do not radiate (in general, low frequencies do not radiate efficiently and require physically large antennas)
- Therefore, move the signal frequencies to a higher frequency, f_c, called the carrier. This process is call frequency translation, mixing, or modulation



- Example: wireless local area networks (WLANs), f_c = 2.45 GHz, BW = 96 MHz

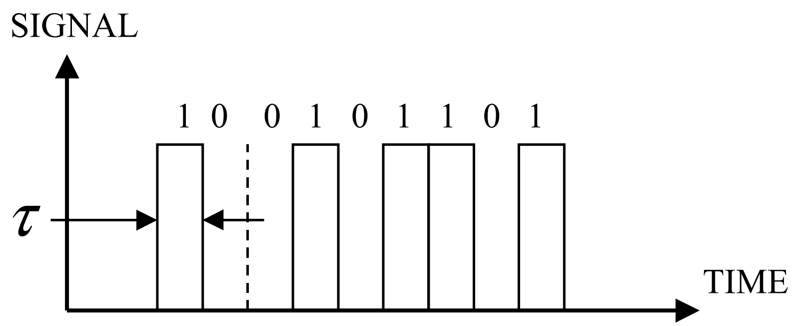
Data Rate and Bandwidth (1)

- The range of frequencies required to "adequately" represent the signal is its <u>bandwidth</u> (BW).
- What is "adequate" depends on the application. For any given application there are many tradeoffs possible.
- Bandwidth is an extremely valuable resource (controlled by the Federal Communications Commission, FCC, in the US).
- Generally, increasing the bandwidth increases the rate of information transmission.
- High frequency bandwidth systems have high <u>data rates</u> (measured in bits per second, bps).
- Consequently the term bandwidth is used interchangeably with data rate (even though it is an incorrect use of a precisely defined term).

Data rate	Bits per second (bps)	Bandwidth
Low	<2400	Narrow
Medium	2400 to 64000	Voice
High	> 64000	Wideband

Data Rate and Bandwidth (2)

- Consider a stream of bits (binary digits) comprised of zeros and ones. A high voltage represents a “1” and no signal represents a “0”.
- The smaller the bit size (width of the pulse in time, τ), the more bits can be packed into a fixed interval of time, and hence a higher bit rate.

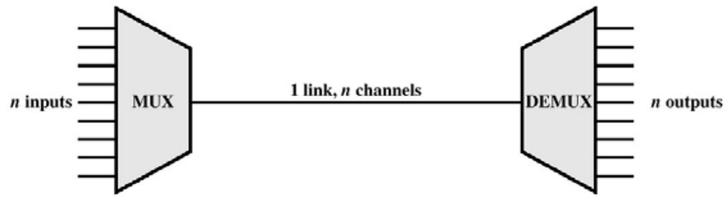


- As shown previously, shorter pulses (bits) have more frequencies, and therefore require more bandwidth.
- This explanation is oversimplified, but illustrates the fundamental tradeoffs.

Multiplexing (1)

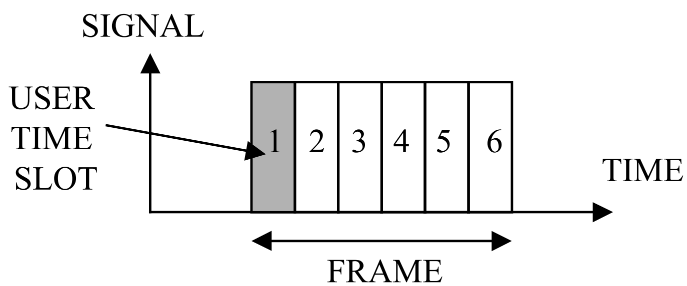
- Multiplexing (combining) and de-multiplexing (separating) are used to increase the capacity of a communication network when there are multiple users.

MUX = multiplexer

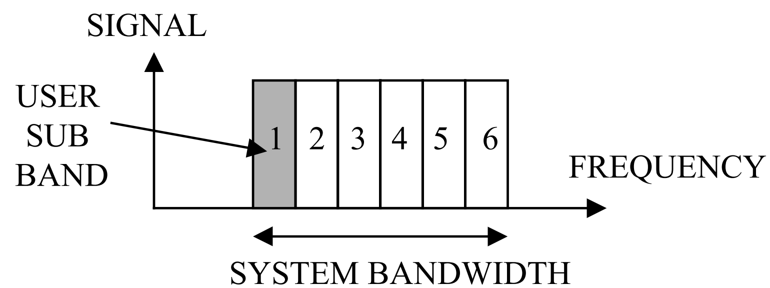


DEMUX = de-multiplexer

- Signals can be combined in the time domain (time slots for each user) or frequency domain (sub-band for each user).



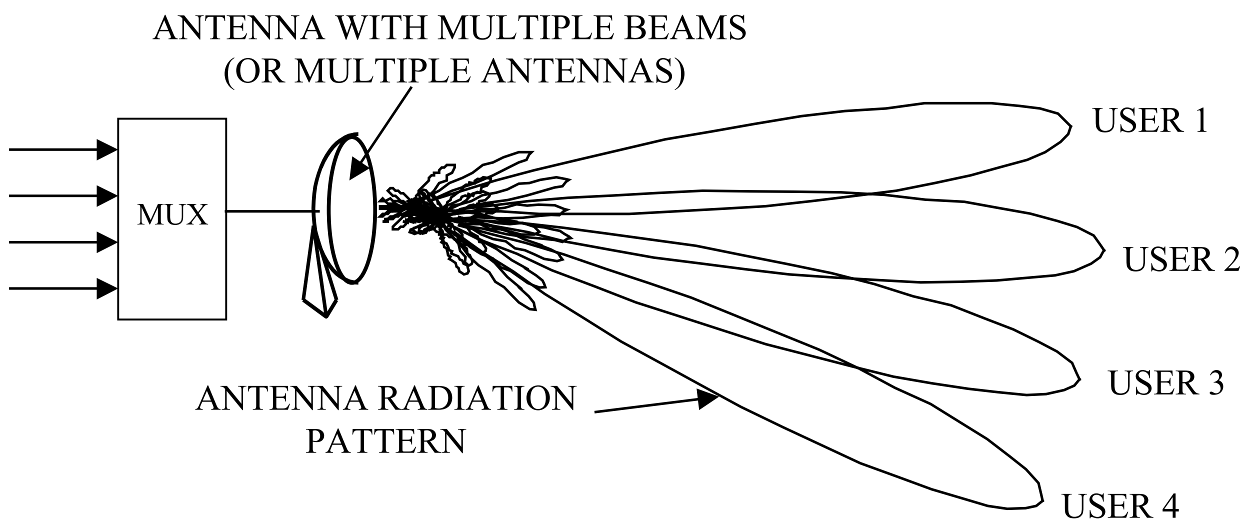
Multiplexing in time (Time division multiple access, TDMA)



Multiplexing in frequency (Frequency division multiple access, FDMA)

Multiplexing (2)

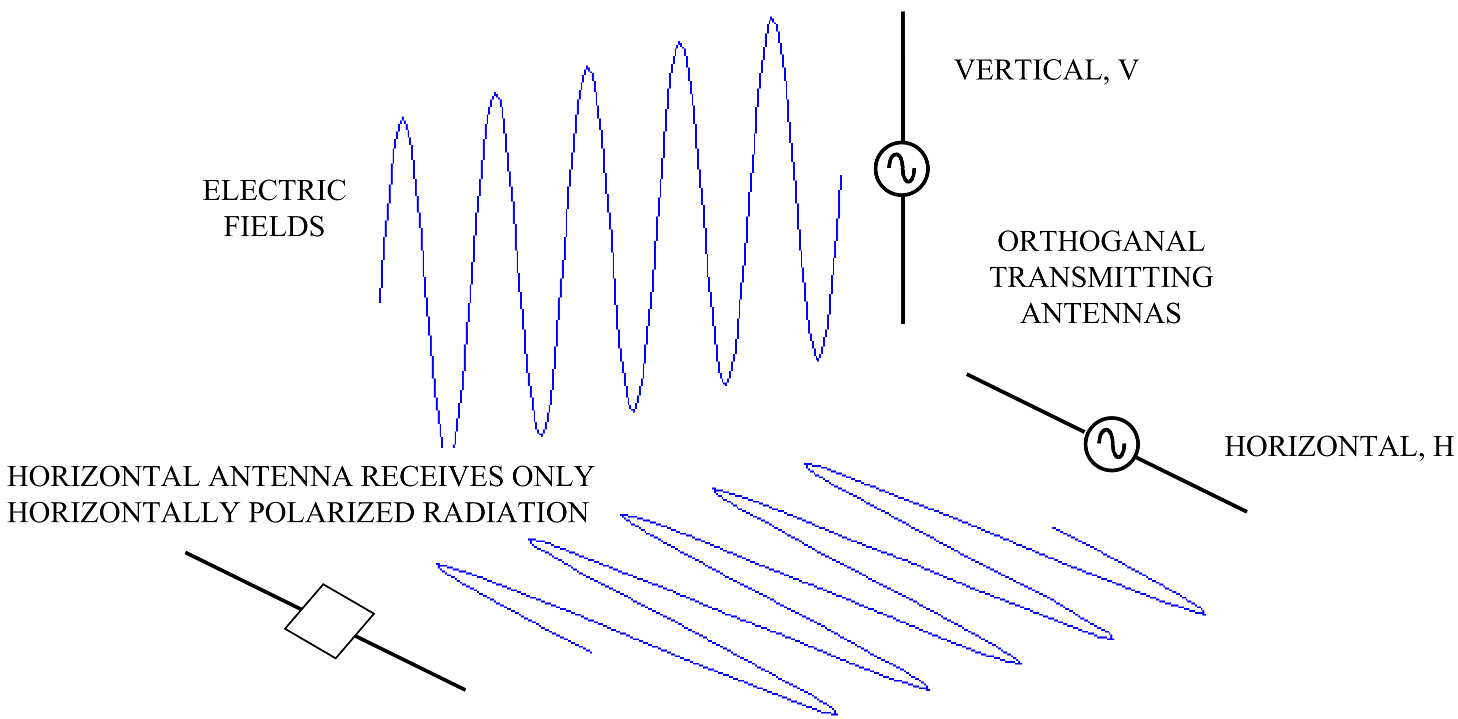
- Another possibility is spatial multiplexing, which can only be done if the users are spatially separated (used in cellular systems).



- There is also code division multiplexing. Each user's signal is modulated with a unique digital code that does not interfere with other users sharing the channel.
- The terms "diversity" and "reuse" are also used for some multiplexing techniques.

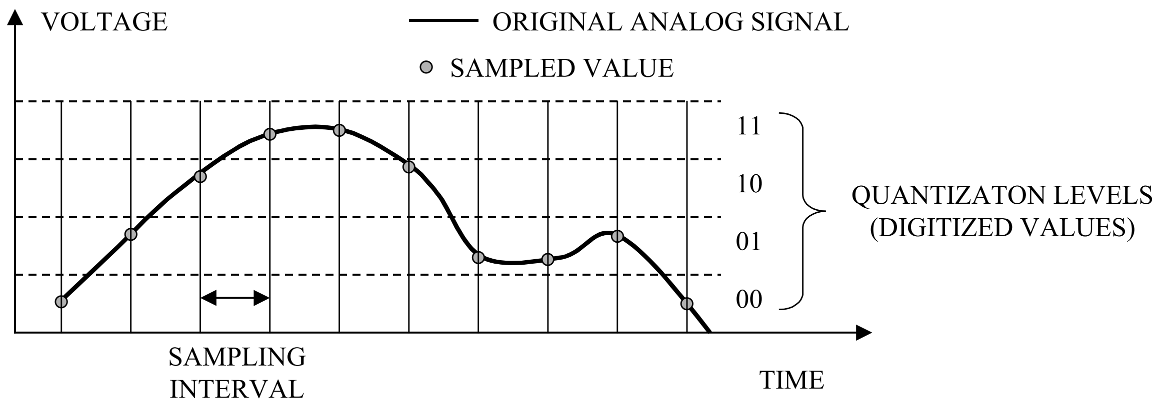
Multiplexing (3)

- Two antenna polarizations can be used to double the number of channels.
- Multiple reflections tend to mix the polarizations. Therefore this technique is only useful in environments free of severe "multipath" (e.g., satellite links, not urban areas).

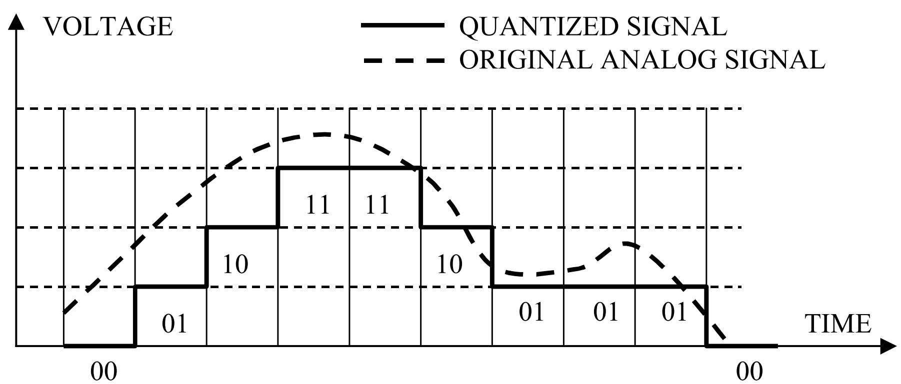


Example of Sampling and Encoding (1)

- Example of sampling an analog signal: 2 bits gives $2^2 = 4$ quantization levels that are given in binary form by 00, 01, 10, and 11.

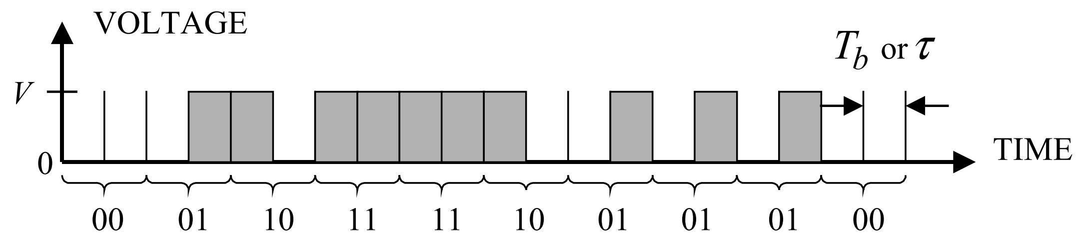


- The quantized signal is shown below (rounding down, or truncation is used here):



Example of Sampling and Encoding (2)

- The binary representation is a bit stream called a line code. The line code is modulated and transmitted.



- General observations:

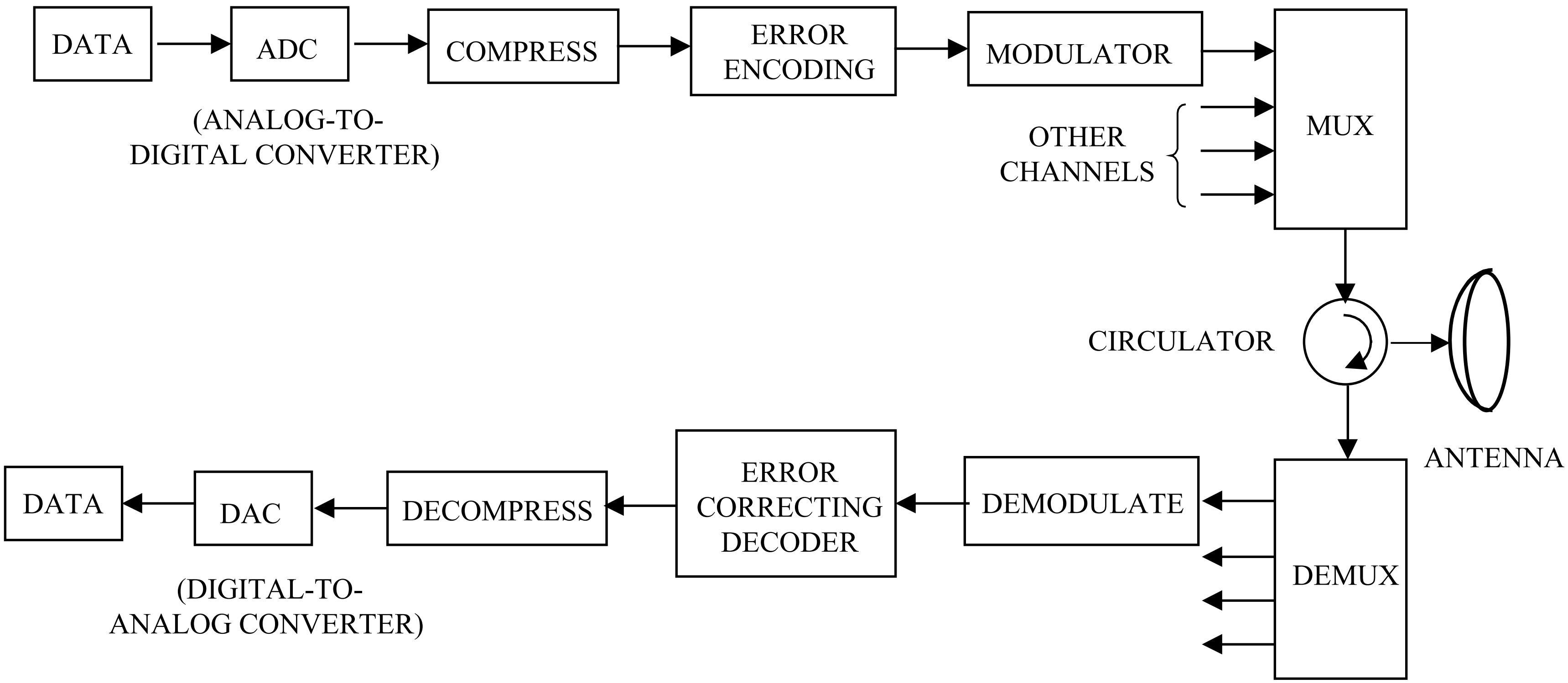
1. The sampling rate must be high enough so that no information is lost (i.e., the quantized waveform must be sufficiently close to the analog waveform).
2. The number of quantization levels (i.e., bits) must be sufficient to represent the original waveform.
3. High sampling rates and more quantization levels increase the length of the line code; hence more time is required to transmit the data resulting in a lower data rate.
4. The transmission time of the line code can be reduced by reducing τ, which requires more bandwidth, as demonstrated previously.

Performance Measures

- In practice (i.e., the "real world") the processing and transmission of information is corrupted by many factors. They include:
    1. Noise generated in the receiver and collected by the antenna (background noise)
    2. Noise and instabilities in the transmitter frequency and power level
    3. Losses and imperfections in devices
    4. Interference due to other users and the environment (e.g., lightening)
- These factors result in errors in the data at the receiving end.
- Error correction is employed in modern digital transmission systems.
- The most direct measure of performance is the amount of information received correctly.
- Parameters used to evaluate the performance of communication systems include:
    1. <u>Data rate</u>: rate in bits per second that data is communicated
    2. <u>Bandwidth</u>: frequency band required for operation
    3. <u>Noise</u>: level of noise that can be tolerated
    4. <u>Error rate</u>: rate at which errors occur
    5. <u>Other</u>: cost, weight, size, maintainability, etc.
- As might be expected, fewer errors occur when a strong signal is received relative to the noise (high <u>signal-to-noise ratio</u>, SNR).

Generic Block Diagram

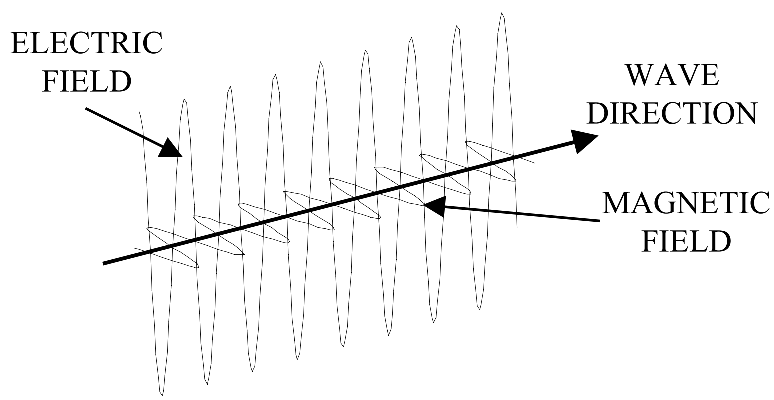
- Wireless system block diagram: (see Ulaby, Figure 1-1)



- A circulator allows simultaneous transmission and reception from a single antenna, unlike a switch.

Electromagnetic Waves

- As the name implies, time varying electromagnetic waves are comprised of electric and magnetic field intensities.



- The fields are vectors: they have a magnitude and direction (similar to the wind, or the flow of water).
- The direction of the electric field vector can be determined by the direction of the force that it exerts on a charged particle, q: $F = qE$ (similar to a particle in water or air).
- Simplified description of the operation of a wire antenna (metal wires have an abundance of free electrons):

  transmitting: an applied voltage forces free electrons in the metal to oscillate, thereby causing radiation

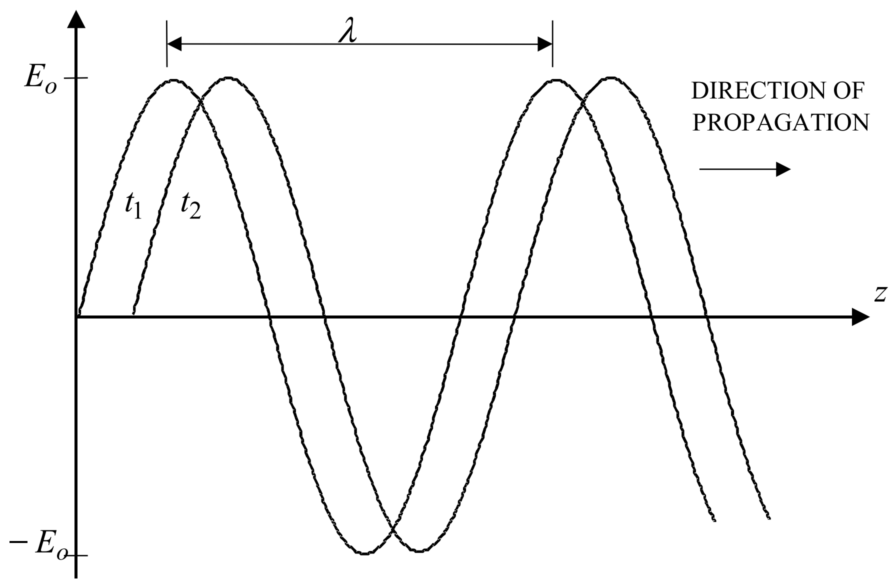
  receiving: the wave impinging on the antenna causes the free charges in the metal to oscillate, inducing a voltage at the antenna terminals.

Plane Waves (1)

- The most basic type of electromagnetic wave is a time-harmonic plane wave, with an electric field intensity of the form

$$E(z,t) = E_o \cos(\omega t - \beta z + \Phi) \qquad \text{volts/meter, V/m}$$

- Time snapshots of the field are shown below $(t_2 > t_1)$.



- wave propagates in the $+z$ direction
- $\lambda =$ wavelength (m)
- $\omega = 2\pi f$ (radians/sec)
- $f = c/\lambda =$ frequency (Hz)
- the phase velocity in free space is
  $c = \omega/\beta \approx 3\times10^8$ (m/s)
- maximum amplitude of the wave is E_o
- there are 2π radians per wavelength
  $\beta = 2\pi/\lambda$
- Φ is the phase shift (radians)

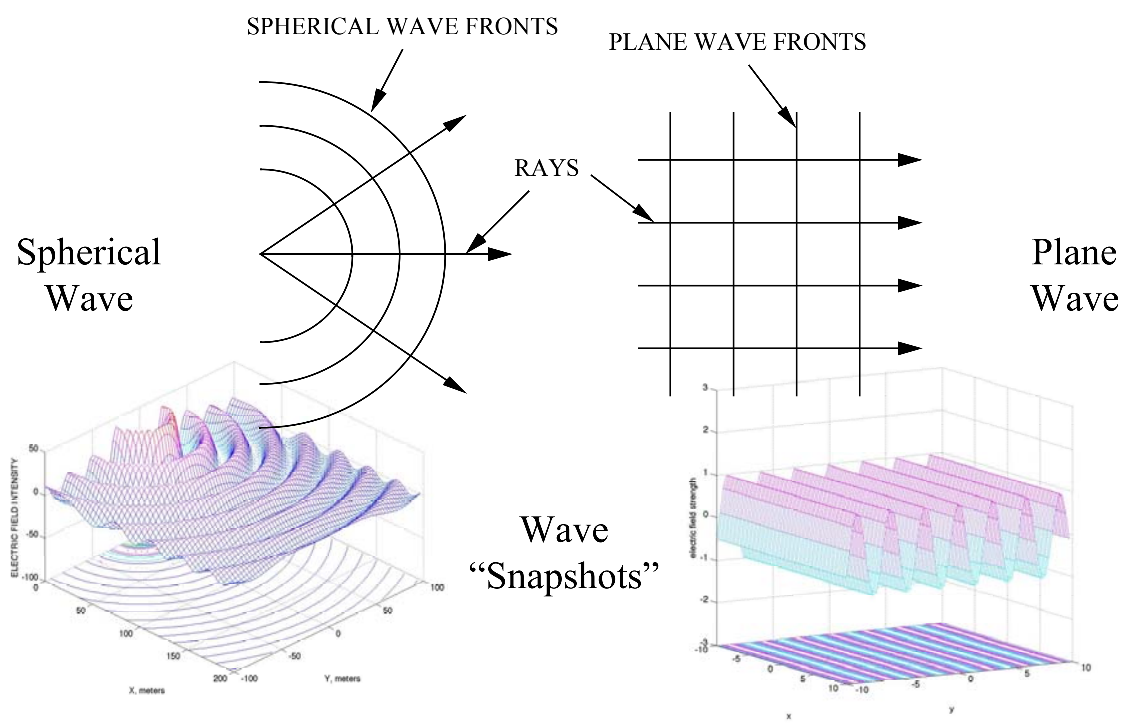
Some Wavelength Calculations

- Communication and radar bands are spread over an extremely wide range of frequencies. (See the spectrum chart at the end or Figures 1-15 and 1-16 in Ulaby.)
- One proposed system for communicating with submerged submarines (Project Sanguine) operated at 70 Hz. At this frequency the wavelength is 4.28 million meters = 4,286 km = 2,571 miles. A natural rock formation stretching over the states of Wisconsin and Michigan was to serve as the antenna. The data rate ranged from 1 bit/s to 1 bit/10,000s.
- "Ham" radio bands cover segments in the range of 1.8 MHz to 50 MHz. The corresponding range of wavelengths is 166.7 m to 6 m.
- Wireless devices operate in the ISM bands, one of which is at 2.45 GHz, where the wavelength is 0.1224 m = 4.82 inches.
- Typical satellite ground station uplinks operate at 14 GHz (2.14 cm wavelength) and the satellite transmitter (downlink) operates at 12 GHz (2.5 cm wavelength).
- Some conversions:

Some conversions:	1 inch = 2.54 cm = 0.0254 m	1 km = 0.62 mile
	1 mile = 5280 feet	3.3 feet = 1 m

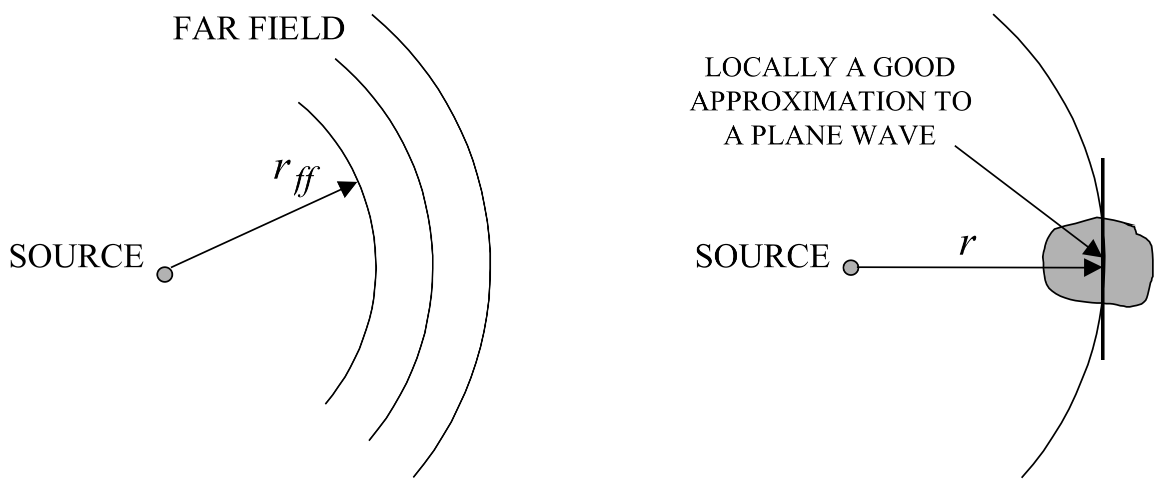
Wave Amplitude

- Plane wave behavior is an accurate representation of propagation on transmission lines.
- Spherical waves propagate outward from the source and have the following form:
  $E(r,t) = \frac{E_o}{r}\cos(\omega t - \beta r)$ where r is the distance from the source.
- Spherical waves are the three-dimensional extension of rings of water waves (the wavefronts are spheres, rather than rings on a surface, Figure 1-10 in Ulaby).
- A comparison of plane and spherical wave representations is shown (time snapshots).



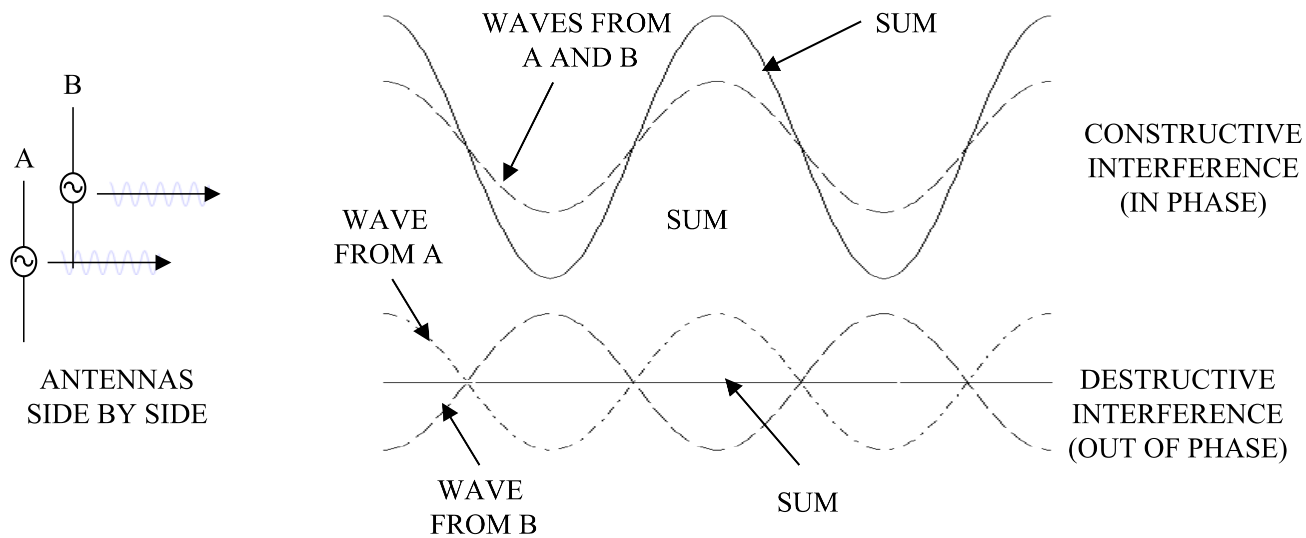
Plane Wave Approximation of a Spherical Wave

- A shown, rays are used to represent a propagating wave. They are arrows in the direction of propagation and are everywhere perpendicular to the equi-phase planes (wavefronts).
- The behavior of rays upon reflection or refraction from boundaries is given by a set of rules which form the basis of geometrical optics (the classical theory of ray tracing).
- If an observer gets far enough from a finite source of radiation (i.e., an antenna), then the wavefronts become spherical.
- At even larger distances the wavefronts become approximately planar on a local scale.



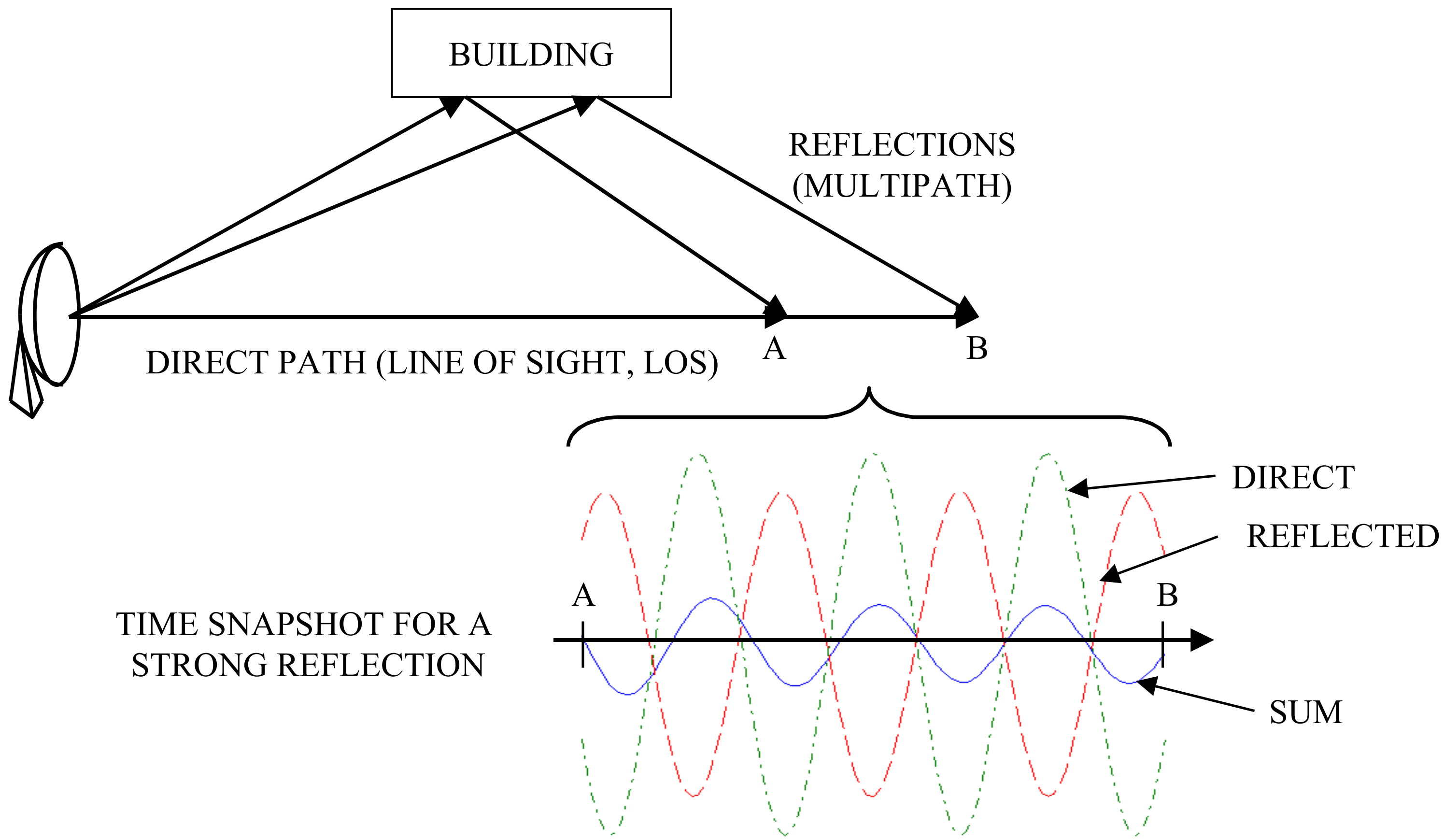
Superposition of Waves

- If multiple signal sources of the same frequency are present, or multiple paths exist between a source and receiver, then the total signal at a location is the sum (superposition principle).
- The result is interference: constructive interference occurs if the waves add; destructive interference occurs if the waves cancel.
- Example: two antennas radiating in the same direction, but with different phase shifts:



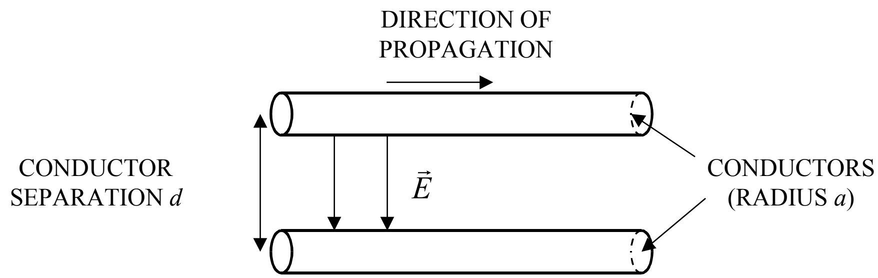
Multipath

- Multipath is an example of interference

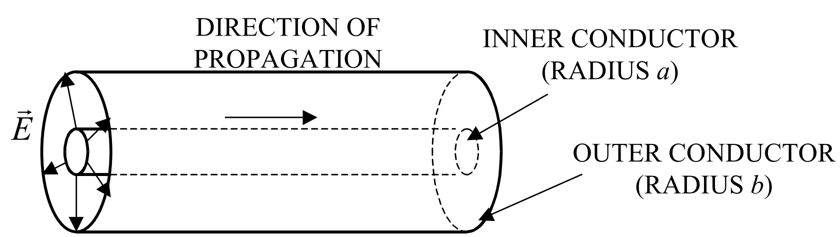


Common Transmission Lines

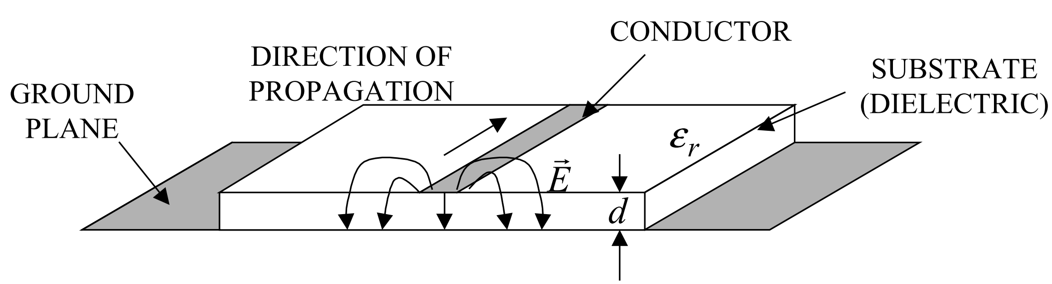
Twin lead or two-wire



Coaxial ("coax")



Microstrip



Dimensions, Units and Notation

- International System of Units (SI, also referred to as MKS, Table 1-1 in Ulaby)

Dimension	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Amount of substance	mole	mol
Temperature	kelvin	K

- Multiple and submultiple prefixes (see Table 1-2 in Ulaby)

Prefix	Symbol	Magnitude
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}

Prefix	Symbol	Magnitude
milli	m	10^{-3}
micro	P	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

Decibel Unit

- In general, a dimensionless quantity Q in decibels (denoted Q_{dB}) is defined by

$$Q_{\text{dB}} = 10\log_{10}(Q)$$

Q usually represents a ratio of powers, where the denominator is the reference, and $\log_{10}$ is simply written as log. Characters are added to the "dB" to denote the reference quantity, for example, dBm is decibels relative to a milliwatt.

- Therefore, if P is in watts: $P_{\text{dBW}} = 10\log(P/1)$ or $P_{\text{dBm}} = 10\log(P/0.001)$
- Antenna gain G (dimensionless) referenced to an isotropic source (an isotropic source radiates uniformly in all directions, and its gain is 1): $G_{\text{dB}} = 10\log(G)$
- Note that:
  1. Positive dB values > 1; negative dB values < 1
  2. 10 dB represents an order of magnitude change in the quantity Q
  3. When quantities are multiplied their dB values add. For example, the effective radiated power (ERP) can be computed directly from the dB quantities:

$$\text{ERP}_{\text{dBw}} = (PG)_{\text{dBw}} = P_{\text{dBw}} + G_{\text{dB}}$$

Note: The ERP is also referred to as the effective isotropic radiated power, EIRP.

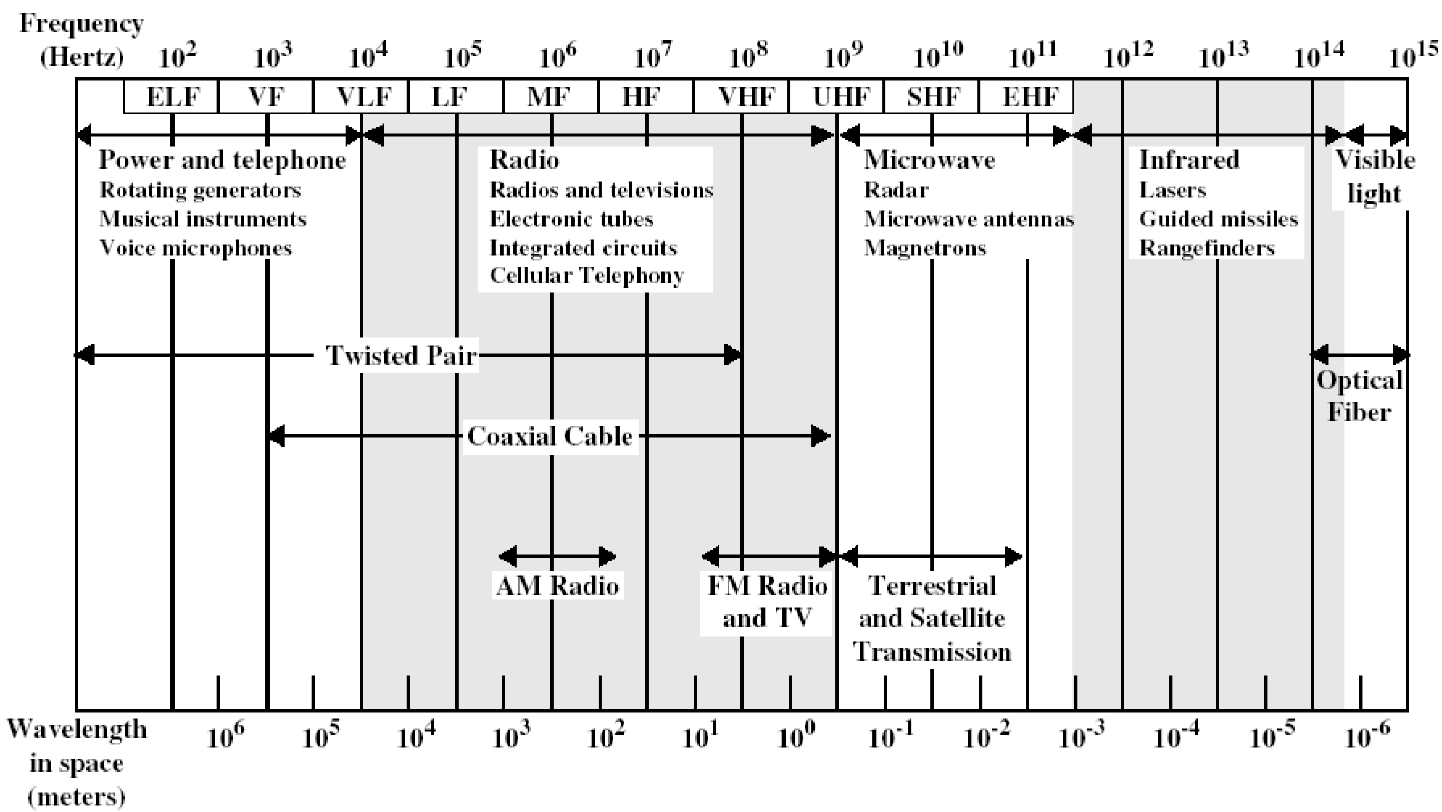
Sample Decibel Calculations

1. A transmitter puts out 35 W. What is the output power in decibels?
   answer: $10\log(35) = (10)(1.544) = 15.44$ dB (generally dB implies dBW), or since 35 W is 35000 mW, $10\log(35000) = (10)(4.544) = 45.44$ dBm (or simply add 30 dB to the dBW value)

2. A receiver has a sensitivity of –120 dBm. (a) How many dBW is this? (b) How many watts?
   answer: (a) $-120\,\text{dBm} - 30\,\text{dB} = -150\,\text{dBW}$
   (b) $10^{-150/10} = 10^{-15}$ W = 1 fW (femtowatt)

3. The light intensity at the input of a 10 m optical fiber is 2 W. The fiber loss is 0.2 dB/m. (a) what is the input power in dBm, (b) what is the output power in dBm, (c) what is the output power in watts?
   answer: (a) $10\log(2/0.001) = (10)(3.3) = 33\,\text{dBm}$
   (b) $(10\,\text{m})(0.2\,\text{dB/m}) = 2\,\text{dB}$ of total loss. Loss implies a negative dB quantity, therefore, the output power is 33 dBm – 2 dB = 29 dBm
   (c) $10^{29/10} = 10^{2.9}\,\text{mW} = 794.3\,\text{mW} = 0.794\,\text{W}$

Electromagnetic Spectrum



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

(From W. Stallings, *Wireless Communications and Networks*, Prentice Hall)

Open Systems Interconnection (OSI) Model

- Developed as a model for computer protocol architecture and as a framework for developing protocol standards.
- Numbered 1-7 from the bottom (e.g., the physical layer is level 1).